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The dark side of star formation in galaxy clusters: spectroscopic follow-up of clusters observed with ISOCAM

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Abstract. The evolution of galaxies in cluster environments can be studied using mid-IR observations which trace star forming regions hidden by dust. The optical follow-up of A1689 (z=0.2), observed at 6.7 and 15 μm by ISOCAM, have revealed a systematic excess of the B-[15 μm] galaxy color distribution with respect that of Coma and Virgo clusters. This result suggests the existence of a dark side of the Butcher-Oemler effect measured in the optical. We present an analysis of the optical/mid-IR properties of the mid-IR emitters in A1689, comparing in particular the star formation rates based on mid-IR and optical data. Morover, we present preliminary result for J1888, a cluster at $z = 0.56$ deeply observed with ISOCAM, based on recent VLT/FORS and NTT/SOFI observations.

1. Introduction

Since the classical study of Butcher & Oemler (1984) who put in evidence an increasing fraction of blue, presumably star-forming, galaxies as a function of cluster redshift, several authors have tried to estimate the importance of the cluster environment on the evolution of cluster galaxies. Recent studies with sample of distant clusters (Dressler et al. 1999, Balogh et al. 2000) pointed out that the star formation rate (SFR) per cluster galaxy appears to be lower than that in similar types of galaxies in the surrounding field. The main drawback of these studies is that the SFR rely on measurements of optical line fluxes (usually [OII] or in a few cases Hα) which suffer from strong dust extinction. Since dust obscuration depends on object types and on environmental conditions, it is impossible to correct it on average. On the other hand, although galaxies affected by extinction show typical spectral features (see Dressler et al. 1999), it is quite impossible to quantify the total SFR on the basis of the optical data alone. Mid-IR surveys, along with radio centimetric fluxes, provide the best estimates of the dust obscured SFR (see e.g. Chary & Elbaz 2001) when far-IR are not available. For this reason a sample of 10 clusters at different redshift ($0.1 < z < 0.9$) has been observed with the ISOCAM camera on-board ISO. We

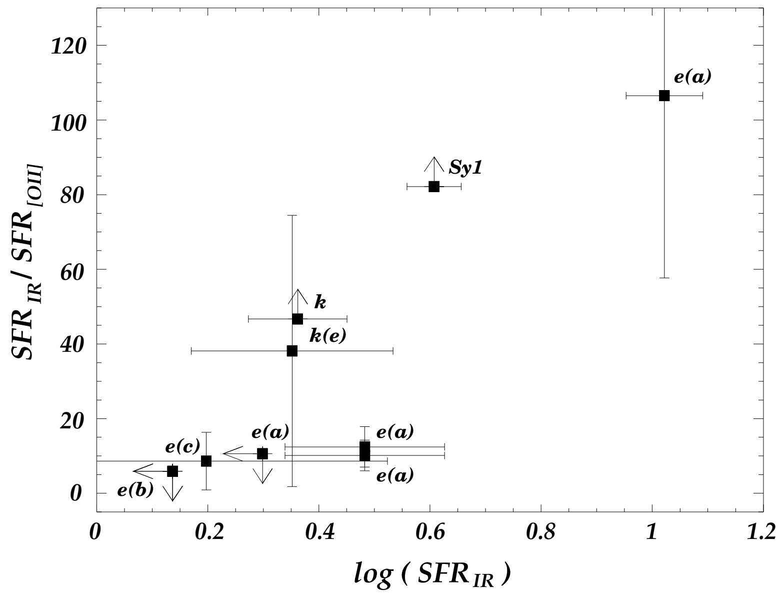

Figure 1. Ratio of the mid-IR to optical SFR estimates versus the mid-IR based SFR estimate for A1689. Note the high dust extinction in some apparently passive galaxies ('k' type).

present here the optical/mid-IR properties of the galaxies detected at 15 μm in the A1689 cluster (see Fadda et al. 2000 for ISOCAM data) and preliminar results of the VLT follow-up program of J1888, a cluster at $z = 0.56$ deeply observed with ISOCAM.

2. Hidden star formation in A1689

Using available images (HST and NTT) and about 100 spectra measured with the NTT (Duc et al. 2001), we studied membership, morphologies and spectral types of the objects detected by ISOCAM in A1689. Our analysis confirms the high fraction of blue galaxies in the cluster (already detected by Butcher & Oemler 1984) relying on a secure cluster membership of the galaxies (spectroscopic and photometric redshifts are known for all the galaxies observed). Most of the 15 μm sources are luminous, blue, emission-line or morphologically disturbed galaxies, i.e. a population of galaxies usually associated with the "Butcher–Oemler" effect. However, $\sim$30% of the 15 μm sources do not show any sign of star-formation activity in their optical spectrum. More of 70% of the emission-line galaxies in our spectroscopic sample are detected at 15 μm and all the galaxies classified as dusty starbursts ("e(a)" type in Dressler et al. 1999) are 15 μm sources. On the contrary, none of the galaxies with a post-starburst optical spectrum have been detected at 15 μm.

Since the AGN activity is very low in A1689, the 15 μm flux is a reliable tracer of the dust-obscured star formation activity (see Chary & Elbaz 2001). Comparing the SFR based on the mid-IR (15 μm flux) and optical ([OII] line flux), we found that for galaxies with mid-IR emission the ratio

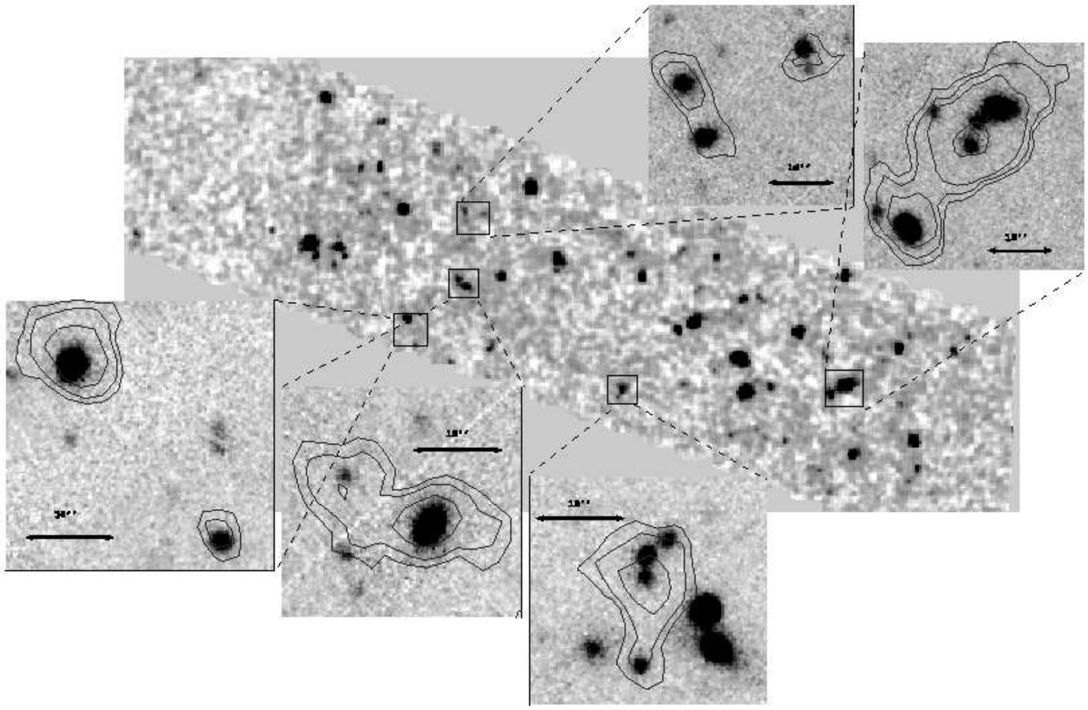

Figure 2. 15μm map of J1888 with more than 100 sources detected. Subsets show 15μm overlays on optical images. Note the excellent astrometric precision of ISOCAM and the clear optical identifications.

SFR(IR)/SFR(Opt) is very high and ranges between 10 and 100, being the highest among "e(a)" galaxies (see Figure 1). The median SFR(IR) is 2 $M_{\odot} yr^{-1}$, while the median SFR(Opt) of the [OII] detected galaxies is 0.2 $M_{\odot} yr^{-1}$. Although we are not observing luminous infrared galaxies (the highest total IR luminosity 6.2×10^{10} $L_{\odot}$ is measured in a "e(a)" galaxy), we conclude that a significant portion of the star formation activity is visible only using mid-IR data. At least 90% of the star formation is missed when estimated from the [OII] line. A comparison with the field, essential to investigate the effects of the environment on the star formation of the cluster galaxies, will be possible only when a statistical sample of mid-IR galaxies for the coeval field of A1689 will be available.

3. Preliminary results in J1888

J1888, a cluster at $z = 0.56$, has been surveyed by ISOCAM at the same depth of the Hubble Deep Field covering a strip of $14.5' \times 3.5'$ crossing the cluster center in order to explore possible variation of the mid-IR properties with the cluster-centric distance (see Figure 2). We have recently obtained about 120 spectra

with VLT/FORS1 and a Ks image with NTT/SOFI, which complements B and R images obtained with the 2.2m ESO telescope. So far we have redshifts for 55 out of 70 sources detected at 15 μm and 22 out of 47 sources detected at 6.7 μm.

The redshift distribution of the cluster, which appears very loose in the optical images, peaks at $z = 0.56$ but the field is highly polluted by background galaxies. Considering the range of magnitudes of the cluster members (21.4 $< B <$25.3), 55% of the galaxies do not belong to the cluster. Considering only the 15 μm sources, only 30% of the ISOCAM sources are cluster members.

The color-magnitude relation is not obvious to determine even for cluster members. Quite surprisingly there is a large number of "red outliers" ($B - R > 2$) which belong to the cluster and most interestingly several of them are detected at 15 μm. The presence of "red outliers" is not uncommon in clusters at $z \sim 0.5 - 0.6$ (see e.g. Margoniner & de Carvalho 2000) but in this case any contamination by field galaxies is ruled out. Contrary to the case of A1689, we have almost no mid-IR emitters among blue cluster members.

On the basis of VLT spectra we did a classification of galaxies according to the scheme of Dressler et al. (1999). As in the case of A1689, we detect at 15 μm all the dusty starbursts ("e(a)" type) and no post-starburst galaxies. Compared to A1689, we detect a larger fraction of spiral-like spectra which is not unexpected for clusters showing the "Butcher-Oemler" effect.

A detailed reanalysis of the J1888 ISOCAM data is now in progress using the new method developed by Lari et al. (2001) in parallel with the analysis of the deep ISOCAM surveys in the region of the Lockman Hole. The comparison of the data from this survey, whose redshift distribution peaks at redshift of 0.6 close to that of J1888, will be fundamental to study the influence of cluster environment on the evolution of galaxies.

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